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# Use of Recirculating Ventilation with Dust Filtration to Improve Wintertime Air Quality in a Swine Farrowing Room

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## Abstract

The performance of a recirculating ventilation system with dust filtration was evaluated to determine its effectiveness to improve the air quality in a swine farrowing room of a concentrated animal feeding operation (CAFO). Air was exhausted from the room (0.47 $m^3sec^{-1}$; 1000 cfm), treated with a filtration unit (Shaker-Dust Collector), and returned to the farrowing room to reduce dust concentrations while retaining heat necessary for livestock health. The air quality in the room was assessed over a winter, during which time limited fresh air is traditionally brought into the building. Over the study period, dust concentrations ranged from 0.005 to 0.31 mg $m^{-3}$ (respirable) and 0.17 to 2.09 mg $m^{-3}$ (inhalable). In-room dust concentrations were reduced (41% for respirable and 33% for inhalable) with the system in operation, while gas concentrations (ammonia [$NH_3$], hydrogen sulfide [$H_2S$], carbon monoxide [CO], carbon dioxide [$CO_2$]) were unchanged. The position of the exhaust and return air systems provided reasonably uniform contaminant distributions, although the respirable dust concentrations nearest one of the exhaust ducts was statistically higher than other locations in the room, with differences averaging only 0.05 mg $m^{-3}$. Throughout the study, $CO_2$ concentrations consistently exceeded 1540 ppm (industry recommendations) and on eight of the 18 study days it exceeded 2500 ppm (50% of the ACGIH TLV), with significantly higher concentrations near a door to a temperature-controlled hallway that was typically often left open. Alternative heaters are recommended to reduce $CO_2$ concentrations in the room. Contaminant concentrations were modeled using production and environmental factors, with $NH_3$ related to the number of sow in the room and outdoor temperatures and $CO_2$ related to the number of piglets and outdoor temperatures. The recirculating ventilation system provided dust reduction without increasing concentrations of hazardous gases.

### Keywords

Swine confinement; ventilation; air quality; air pollution control; recirculation

## Introduction

Over the past few decades, livestock production in the U.S. has shifted from the traditional small–scale (<50 head) to large-scale production using concentrated animal feeding operations (CAFOs). In 2012, 68% of US hogs were produced on farms with 5000 or more

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animals, and 90% occurred on farms with 2000 or more, both increases over 2007.[1] CAFOs house animals in large buildings, typically with under-floor manure pits to accumulate animal excretions in hog and cattle units. Air above the manure pits, and below the floor, is mechanically exhausted to the outdoors to minimize gas concentrations in the building. Additional room ventilation systems are incorporated into building designs to remove heat during the warm summer season, where radial fans exhaust indoor air to maintain optimized temperatures for animal health.[2] However, in the winter, particularly in the Midwest, ventilation inside CAFO is minimized to reduce heating costs, resulting in the buildup of contaminants.

Many hazardous compounds are present in swine CAFO. Studies have examined CAFO worker exposures to dusts,[3-6] endotoxin,[7-12] and hazardous gases including hydrogen sulfide ($H_2S$) and ammonia ($NH_3$),[13-15] many looking at multiple contaminants simultaneously. Within a given production site, personal exposures to these compounds are less associated with work tasks than with season,[3] although room concentrations of particulates are known to vary with factors such as feed type and delivery method.[16-18] In large buildings, concentrations are known to vary spatially[6,19] and seasonally.[20-23]

Poor air quality inside swine CAFOs is associated with adverse health effects among workers. Declines in lung function have been noted by many,[24-30] including significant cross-shift changes.[24, 26, 28] A dose-dependent decline in $FEV_1$ was reported with exposures to endotoxin in dust.[25,26] Self-reported respiratory symptoms, such as chronic cough and phlegm, are more prevalent for CAFO workers than for controls,[25, 27, 31-35] with particular note of respiratory symptoms increasing with increased years of work in CAFO.[7] Measures of respiratory inflammation using bronchoalveolar lavage, specifically increased lymphocytes and neutrophils, have been identified both in healthy workers exposed to swine dust[36] and in farmers.[37] Hence, a large body of literature has identified that swine CAFO workers are at risk of developing adverse respiratory symptoms and disease.

High exposures, combined with known health declines, indicate the need to control exposures. Attempts to reduce room concentrations by altering production processes include misting oil to suppress dust[29, 38-40] and changing disinfection protocols.[41] However, these control measures have not been adopted by swine producers in the upper Midwest. As an alternative, workers in CAFOs are advised to wear respirators, particularly N95 filtering facepieces[3, 42], but the adoption of respiratory protection by hog farmers remains low.[43-45]

Ventilation represents another way to improve the air quality and health of workers in swine CAFO. In the upper Midwest US, a successful ventilation system must control concentrations of hazardous contaminants in winter when dilution with fresh air is minimized to save heating costs and exposures are high. Studies investigating the effects of increasing manure pit exhaust reported their inability to reduce concentrations in the swine farrowing rooms to healthy levels.[46,47] While helpful to reduce contaminant concentrations in most seasons, the concentrations of gram-negative bacteria[46] or dust and ammonia[47] were reduced, but not below concentrations recommended to protect health.

Simulation studies indicate that a recirculating ventilation system that incorporates contaminant removal can be effective to control hazardous concentrations in a swine farrowing room. [48,49] Changes in air quality were simulated for multiple air-cleaners (e.g., filtration, cyclonic, electrostatic, wet-gas devices) over a range of ventilation rates and dilutions with and without clean, outdoor air. The simulations identified operational parameters for the livestock industry, indicating field deployment was feasible. The simulations specifically identified that the tradeoff of diluting treated room air with cold, outdoor fresh air resulted in additional contaminant generation associated with increased heater operation, and significantly increased heating costs, so that field deployment should focus on 100% recirculation system.

The goal of this study was to assess the performance and field viability of a recirculating ventilation system to improve air quality in a swine farrowing room.

## Methods

### Site Description

This study was performed over the 2013-14 winter season from Dec. 13 to February 27 at the large swine farrowing room at the Mansfield Swine Education Center at Kirkwood Community College (Cedar Rapids, IA). Figure 1 illustrates the layout of this 19-sow capacity room. Row I, II and IV contained five crates each (1.5 m by 2.4 m) and Row III contained 4 larger crates (2 m by 2.4 m). The room had two under-floor manure pits, one for Rows I and II and the other for Rows III and IV. Each 0.91-m-deep pull-plug manure pit was vented by a 0.41 $m^3 s^{-1}$ exhaust fan, located outside the building along the west wall. The north, west and south walls were exterior; the east wall separated the farrowing room from a heated hallway. The room had four radial exhaust fans, two on the north and two on the south walls, which were closed throughout the study and, by January, were sealed with plastic. Eight ceiling-mounted louvered vents (Bi-Flow; RayDot Industries, Cokato, MN) were positioned between Rows II and III and remained closed throughout the study; gaps and holes in louvers were not sealed as they represented conditions found in other production barns. Two single-unit, pressure-activated louvers (1.17 m wide) lined the east wall and allowed heated air from the hallway to enter into the test room; these louvers were often propped open approximately 2 to 5 cm help heat the farrowing room. One gas-fired heater (AW060, Guardian 60, L.B. White Co., Onalaska, WI) was positioned in the room above the eastern crate in Row II, angled with the hot air exhausted toward the south west corner of the room.

Sows were moved into their crates prior to delivering piglets and were positioned with heads toward the aisles between Rows I & II and Rows III & IV. Piglets remained in the room for 21 to 28 days before being moved into the nursery, although young piglets were occasionally moved between crates to even out nursing requirements. At one point in this study, all sows and piglets were relocated into a smaller farrowing room, and sampling on one of these days (Dec 31-Jan 1) was conducted to assess the room air quality without swine.

## Ventilation and Control Equipment

A pocket-filter-type air pollution control device (Figure 2, Shaker Dust Collector [SDC], model SDC-140-3, United Air Specialists, Inc., Cincinnati, OH) was selected to treat room air. Positioned outside the west wall of the building (Figure 1), the fan pulled 0.47 $m^3 s^{-1}$ (1000 cfm) from the farrowing room through a 14-pocket standard polyester sateen filter (United Air Specialists, Inc) inside the SDC and then pushed filtered air back into the building (Figure 2). The pressure drop across the SDC was logged every minute to track filter loading, and dust concentration in the supply and return air ducts was measured with a DustTrak (Model 8534, TSI, Shoreview, MN) to estimate the SDC efficiency.

Air within the room was collected at two 8-inch (0.203 m) galvanized round ducts, positioned at the height of the crates (0.635 m on center) and at the center of the sow head aisles ((Figure 1). This air was moved through the SDC, and then filtered air was returned to the room through a 10-inch (0.254 m) duct. Inside the center of the building, the return air was split to deliver half the volume to each of two 10-inch (0.254 m) diameter fabric air diffusers (Softflow Diffusers, Air Distribution Concepts, Delvan, WI) suspended above the head-aisles. The position of the diffusers was selected to provide the cleanest air where workers spend the most of their time when in the room and to minimize airflow on the crated animals.

## Sampling Methods

Twenty-four hour monitoring was conducted throughout the study period at six fixed positions, indicated as A through F in Figure 1. A pole was mounted at each position (Figure 3), located approximately 2.7 m away from the east and west walls, with eye-bolts positioned 1.5 m above the floor to indicate the position of sampler inlets.

Table I summarizes the monitoring equipment deployed. All direct-reading instruments and airflow pumps were powered by 110V wall power to accommodate 24-hour sampling. All equipment was deployed at each of the six stations except for temperature and humidity data collected with the VelociCalcs, which were deployed only at Positions C and D (center aisle). While most monitors were deployed at each of the six locations every day, the VRae at Position F was removed from service during the study, resulting in only nine of the 18 sample days characterizing multiple gases ($O_2$, LEL, $H_2S$, CO, $NH_3$) at this location. Outside temperatures were obtained from meteorological equipment operated by the regional airport (Cedar Rapids, IA), 2.9 miles from the barn. All devices were pre- and post-calibrated in the laboratory for each sampling event. At the site, all direct-reading devices were collocated in the east hallway for at least 10-minutes before and after each 24-hour monitoring period.

Sampling commenced one week after a new herd of sows were introduced into the farrowing room and continued through the barn's winter farrowing season. Sampling was conducted on 18 days from December 13, 2013 to February 27, 2014. The recirculating ventilation system was off for seven (Dec 13-19; Jan 22-27; Feb 26-27) and on (Dec 21-Jan 21; Jan 28-Feb 25) for 11 of the sample days. The recirculating ventilation system was turned on or off at least 24 hours prior to the scheduled sampling day. The number of sows and piglets housed in each crate were recorded at the start and end of each sample period.

## Data Analysis

Downloaded data were assessed for sensor drift based on pre- and post-sampling colocation data. A sensor drift was identified when the collocated concentrations differed by more than 100 ppm for $CO_2$, 1 ppm other gases, or 10% for dust. Linear regression was used to identify slope and intercept between a given drifted sensor concentration and the mean of the collocated concentrations (excluding the drifted sensor(s)). For the drifted sensor, each data point from the 24-hour farrowing room data was adjusted, plotted against other room concentrations to confirm the adjustment was reasonable. The adjusted 8- and 24-hour concentrations for that sensor's Position were reported for that monitoring day. The most frequent adjustment was needed for ammonia sensors (eight of 18 sample days).

Data from direct-reading instruments were processed by shift (three 8-hour shifts per day: Shift 1: 8:30 am to 4:30 pm; Shift 2: 4:30 pm to 12:30 am; Shift 3: 12:30 am to 8:30 am) and by day (24-hours). Gravimetric dust concentrations were computed from filter weight gain and total sample volume. Descriptive statistics (mean and standard deviation [SD]) and the number of days or shifts with concentrations exceeding recommended concentrations for each measure were generated. Descriptive statistics for production factors (swine and sow counts) and environmental factors (outdoor temperature) were also generated. Data and ln-transformed data were assessed for normality using the Shapiro-Wilks p-statistic.

The data were then examined to determine whether the ventilation system altered the room contaminant concentrations. Eight-hour and 24-hour means with the ventilation system off were compared to those with the system on using Wilcoxon two-sample and Kruskal-Wallis test (for non-normal data). Tests examined whether dust concentrations were *reduced* and gaseous concentrations ($CO_2$, $NH_3$) were *not increased* with the use of the new ventilation system.

Next, the uniformity of the concentrations throughout the room was evaluated, by contaminant, using an adjusted Tukey (Tukey-Kramer) multiple comparison of concentration throughout the study room, by ventilation status. Finally, the effect of time of day (“shift”) on contaminant concentrations was examined using multiple comparison tests. Note that all production activities (e.g., feeding) occurred during Shift 1 throughout the study.

A final analysis was conducted to determine whether contaminant concentrations could be estimated from production and environmental factors using linear regression with backwards elimination. Animal housing numbers may be associated with concentrations of dust (feed, animal dander, and animal activity), $NH_3$ (excreted urine, generated in high volume by the sows and to a lesser extent by piglets), and $CO_2$ (exhaled by swine and piglets). Outdoor temperature may be associated with $NH_3$ (released from the under-crate manure pit) and both CO and $CO_2$ (generated by the un-vented propane heaters). Understanding whether production or environmental factors affect contaminant concentrations may identify additional control options to improve CAFO air quality.

# Results

## General Findings

Descriptive statistics for contaminants are presented in Table III. Data from direct-reading instruments are summarized for 8-hr shifts and for 24-hour averages, whereas that from gravimetric samples (inhalable and respirable dust concentrations) are only available for the 24-hour period. Results of normality tests are indicated in this table, with an asterisk indicating that the data were not normally distributed. Normality tests for ln-transformed data were also performed, with limited improvement. Where normal and ln-normal distributions were not confirmed, non-parametric tests were required to evaluate differences for hypothesis testing (difference by ventilation system status, time of day, and position).

Figure 4 illustrates the mean 24-hour concentrations, by date, for dust, $NH_3$, $CO_2$, the main contaminants identified in this field study. The error bars indicate the range of concentrations over the six sample positions within the farrowing room on a given day, with markers indicating whether the ventilation system is on or off. As is shown, inhalable dust concentrations were below the industry recommended limit of 2.8 mg $m^{-3}$ both with the system on and off, but respirable dust exceeded 0.23 mg $m^{-3}$ at a few locations throughout the study, with all samples on the last day of the study exceeding this concentration. Twenty-four hour $NH_3$ concentrations ranged from non-detectable to 30 ppm throughout the study period, with a mean 24-hour concentration of 9.0 ppm (SD = 6.5 ppm). Sixty-two percent of the samples exceeded the 7 ppm industry recommendation, 49% of the time with the ventilation system off and 71% of the time with the system on. On all sample days, the $CO_2$ concentrations exceeded the 1540 ppm industry recommended limit, with eight 24-hour averages exceeding 2500 ppm (50% of the TLV). The minimum 24-hour average $CO_2$ concentration was 1860 ppm, with the maximum reaching 3300 ppm on one of the colder days with high sow but moderate piglet population in the farrowing room (2/10/2014).

The $O_2$ and LEL changed little over the duration of the study. Hydrogen sulfide, a gas of concern when working in CAFO and manure operations, averaged only 0.015 ppm, with the maximum 24-hour average of 0.18 ppm (system on, 2/17/14, a relatively warm day at −1.4° C, with full complement of sows and the second largest piglet population during the study). Carbon monoxide concentrations averaged 1.9 ppm over the study, well below the 25 ppm OEL. Due to low concentrations for $H_2S$, CO and LEL, along with little change in percent $O_2$, no additional evaluation of these four compounds was performed.

Operational parameters varied over the study period. The mean outdoor 24-hr temperature was −9.1°C (SD = 6.7°C), with slightly warmer days when the ventilation system was on (mean = −8.4°C, SD = 6.2°C) compared to when the system off (mean −9.6°C, SD=7.3°C). While the maximum sow capacity of the room was 19, the mean sow count was only 13.1 on days with the system off and 14.0 for the system off. The mean piglet count over all sample days was 68.1 (SD = 35.6), with higher counts with the ventilation system off (73.0, SD = 14.6) compared to the system on (65.0, SD = 44.7). Table IV details sow and piglet occupancy of the four crates nearest each fixed sampling location.

## Effectiveness of Ventilation System

Table V summarizes statistical analyses of the room concentration data, with the first data column presenting tests of ventilation system effectiveness. The parametric tests are in the top half of the table, but, since all of the 24-hour data except the pDR dust concentration data were *not* normally distributed, the non-parametric tests at the bottom of the table should be used to interpret findings. However, both sets of data are provided to demonstrate the similarity of findings between the two methods of analyses.

The mean inhalable dust concentration, over all ventilation conditions, was 0.81 mg $m^{-3}$ (SD=0.41 mg $m^{-3}$). Ten of the 108 samples were unusable, either due to torn filters (3) or pump failures (7). The mean concentration with the ventilation system off was 1.01 mg $m^{-3}$ and was reduced to 0.68 mg $m^{-3}$ with the system on, yielding an overall 33% reduction with the system on. This represents a substantial and significant ($p<0.001$, both Tukey-Kramer and Kruskal-Wallis) reduction in inhalable dust with the recirculating ventilation system on.

Over all ventilation conditions, the mean 24-hour respirable dust concentration, as measured with gravimetric analysis, was 0.15 mg $m^{-3}$ (SD = 0.05 mg $m^{-3}$). Two of the 108 respirable samples were unusable (pump failure). The maximum measured concentration was 0.31 mg $m^{-3}$, and 20 samples were at or below 0.1 mg $m^{-3}$, all of which were on days with the recirculating ventilation system on. The mean concentrations with the ventilation system off (0.20 mg $m^{-3}$) were higher than those with the system on (0.12 mg $m^{-3}$), yielding an overall 41% reduction. This represents a substantial and significant ($p < 0.001$, both Tukey-Kramer and Kruskal-Wallis) reduction in respirable dust with the recirculating ventilation system on.

Over all positions and days, the mean 24-hour respirable dust concentration measured with the direct-reading pDR was 0.05 mg $m^{-3}$ (SD = 1.5 mg $m^{-3}$), approximately one-third the concentration identified by gravimetric samples. For days with the ventilation system off, the mean concentration was 0.07 mg $m^{-3}$ (SD = 0.026 mg $m^{-3}$), with a system on mean of 0.039 mg $m^{-3}$ (SD = 0.014 mg $m^{-3}$). The reduction in dust concentration using the pDR was estimated at 80%, more than was estimated using gravimetric techniques ($p<0.001$, both Tukey-Kramer and Kruskal-Wallis). While these data are useful to look at trends in room concentrations over time, particularly between-shift differences in dust concentration, the pDR readings significantly differed from gravimetric measurements and will not be used to estimate risk of exposure in the room.

Ammonia and $CO_2$ concentrations were used to assess whether the recirculating ventilation system increased gas concentrations over a winter farrowing cycle. Ammonia concentrations averaged 7.8 ppm (SD=4.7 ppm) with the ventilation system off and 9.9 ppm (SD = 7.3 ppm) with the system on, representing an unsubstantial and statistically insignificant difference between the two conditions ($p=0.13$ Tukey-Kramer, 0.22 Kruskal-Wallis). Carbon monoxide averaged 2480 ppm (SD=350 ppm) over the study duration, 2440 ppm (SD = 350 ppm) over days with the ventilation off, and 2500 (SD= 350) ppm with the ventilation on, an unsubstantial and statistically insignificant difference between the two conditions ($p=0.32$ Tukey-Kramer, 0.33 Kruskal-Wallis). Hence, concentrations were not increased by increasing the airflow through the room, important to demonstrate the feasibility of this control option to swine producers.

### Spatial Variability

To investigate whether the locations of the exhaust and return air ducts affected the distribution of contaminants within the room, both 8-hour and 24-hour concentration averages were compared between the six sampling locations (Table V, data columns 2 and 3). While multiple comparison test results are shown for all contaminants, interpretation of data that were not normally distributed (indicated with asterisk) relied on non-parametric analyses.

The concentration of inhalable dust had no significant variation throughout the room. Respirable dust concentrations did not vary spatially with the ventilation system off. However with the system on, statistically significant gravimetric differences were identified from 24-hour average measurements (D = 0.09 mg $m^{-3}$ < E = 0.14 mg $m^{-3}$). Since dust generation is a function of sow and piglet occupancy, examination of whether the crates surrounding these positions was considered as the source of concentration differences. However, the number of sow and piglets in these crates did not support these increased concentrations: Table IV shows crates near F had highest occupancy and those near A and B had the lowest occupancy when the ventilation system was on, indicating that swine population was not the source of the difference between concentrations at D and E. The other factor for increased dust generation is that the concentrations on the head aisles would be higher than those in the tail aisles (positions C and D), as the head side was where feed is dispensed and delivered to the sows. This, combined with the fact that position D was located near the gas-fired heater, where elevated concentrations of small particulates may have resulted in concentrations above that at C, which was not found. Position E was located furthest from the hallway (fresher air) and closest to the exhaust, and a combination of crate occupancy, position along the head aisle, and a natural gradation of low (fresh air) to high (near exhaust ventilation duct) may account for this difference.

Using 8-hour average data from the direct-reading respirable dust monitor, again insignificant differences were observed with the ventilation system off, but with the system on, respirable dust concentrations were significantly lower at position B (0.031 mg $m^{-3}$) compared with both C (0.045 mg $m^{-3}$) and E (0.043 mg $m^{-3}$), although this trend was not significant using 24-hour averaged data presented in Table V. Trends in neighboring occupancy also do not explain these differences. Note that even with concentration differences between these positions, all pDR concentrations were reduced between 31 and 51% from days with the system off.

Twenty-four hour $NH_3$ and $CO_2$ had no positional differences (Table V), but positional differences were identified when considering 8-hour room concentrations. Ammonia at A (10.3 ppm) was statistically different from F (5.6 ppm), near the hallway door that typically left open by workers. Carbon dioxide concentrations were significantly higher at F (mean 2700 ppm) compared to both positions B and C (both mean 2400 ppm), but only with the ventilation system on.

### Temporal Variability

The results from multiple-comparison and non-parametric tests of direct-reading concentrations by shift (8-hour means) are summarized in Table V. Using non-parametric tests, respirable dust was the only contaminant that exhibited differences in concentration by work shift. The mean pDR concentration during the day shift (Shift 1, 0.074 mg $m^{-3}$) was higher than the subsequent evening shift (Shift 2, 0.062 mg $m^{-3}$), which agrees with feeding activity trends observed to occur during the day shifts. The same trend was not identified in the data for which the ventilation system was off. While $NH_3$ differences between day (7.4 ppm) and overnight (9.7 ppm) shifts were significant in multiple comparison tests with the ventilation system off, the more appropriate non-parametric tests identified no significant $NH_3$ difference between shifts.

### Factors Affecting Contaminant Concentrations

Figure 5 presents the most significant relationships between contaminant and production/ environmental factors. Neither temperature nor swine or piglet counts were associated with measured dust concentrations. However, both the number of sows and the outdoor temperature were significant in estimating 24-hour $NH_3$ concentrations, but the piglet count was not. A no-intercept model was also the best fitting $NH_3$ model, indicating that the room concentration was a factor of the number of sows and outdoor temperature, only:

$$NH_3 \quad ppm{=}0.43 \quad (Sow) - 0.50 \quad (Temp \quad {}^{\circ}\mathrm{C}) \quad \left(\mathrm{R}^2{=}0.84\right) \quad (1)$$

As the sow population in the room (range 0 to 19) increased and the outdoor temperature (range −23.9 to +0.2°C) decreased, the $NH_3$ concentration increased. The addition of a factor to indicate whether the ventilation system was on or off was included in this analysis but was determined to be insignificant, consistent with the above finding that ammonia concentrations did not differ by ventilation system operation status.

For $CO_2$ concentrations, the sow count was insignificant, but the piglet count, temperature, and an intercept were significant. Again, the operation of the ventilation system was not a significant factor for estimating the $CO_2$ concentration, in agreement with the preceding analyses finding no change in $CO_2$ as a function of ventilation system status. The best-fitting model to estimate $CO_2$ concentration within this farrowing room was:

$$CO_2 \quad ppm{=}1870{+}3.8 \quad (\mathrm{piglets}) - 38.1 \quad (Temp \quad {}^{\circ}\mathrm{C}) \quad \left(\mathrm{R}^2{=}0.82\right) \quad (2)$$

The intercept indicates that this room has a "background" concentration of $CO_2$ that is well above typical outdoor concentrations (e.g., 400 ppm). Further, each piglet (range 0 to 119) contributed 3.8 ppm of $CO_2$ to the room, and $CO_2$ concentrations increased by 38 ppm for every 1°C drop in outdoor temperature, confirming that the gas-fired heater is likely a substantial and significant contributor to the room $CO_2$.

## Discussion

This work provides critical evidence that incorporating standard ventilation controls in animal production facilities can serve to reduce dust concentrations without increasing concentrations of gaseous contaminants. The recirculating ventilation system used in this study reduced respirable dust concentrations by 41% and inhalable dust by 33%. Although dust concentrations in the room were not particularly high, the reductions seen here are expected to be observed for substantially dirtier operations. The dust filtration system deployed in this study used a new pocket filter, without pre-coating. Over the range of the study, the pressure drop across the filter of the SDC increased from 125 to 249 Pa (0.5 to 1.0 in wg), well below the recommended capacity of the filter (996 Pa, 4.0 in wg). In-duct dust concentration efficiency measurements identified that initial collection efficiency was only 60%, but 95% efficiency was reached by day 30 of system operation. The use of pre-coating may help achieve higher efficiencies when the system is first placed on line.

To increase the likelihood of the agricultural sector adopting this technology, particular attention was given to the heating system throughout the study. The treated air returning into the building was as warm as the room air, and on some days was identified as slightly warmer, possibly due to heating by system's motor/fan unit. This conservation of heat was achievable despite the fact that the air handler and SDC units were housed outside the building. Presumably, insulating the outside ductwork conveying air to and from the building was important to maintain heat.

Limited engineering intervention studies at livestock CAFO are available to guide farmers on methods to reduce contaminant concentrations in the winter, when exposures are at their maximum and energy costs are critical. The recent work of Rule et al.[39] examined the effects of wintertime atomization of an acid-oil-alcohol mixture in a pig finishing barn (670-780 pigs housed) in the Mid-Atlantic region of the US. By atomizing 45 $mL/m^2$ floor area for less than one minute per day, Rule et al. reported reductions of dust concentrations between 70 to 90% for dusts collected with PM2.5 and the 37-mm closed-face cassette. Similar to this SDC filtration study, oil misting showed no ammonia reductions (passive Draeger tubes). Previous studies[38] identified that oil misting using canola oil in swine facilities resulted in slip hazards when application rates of 20 $mL/m^2$ floor area were applied. Rule et al. identified $5,500 to $10,000 installation costs per finishing barn, with oil solution running $0.0011 per square foot and minimal electrical costs. Comparatively, the installation of the SDC unit in the much smaller farrowing room in this current study was on the order of $6000, with maintenance requirements for filter replacements and energy consumption for operating the fan 24-hours per day over the winter season.

The test site's $CO_2$ concentrations (1888 to 3220 ppm, 24-hour mean) exceeded than in recent literature.[13,15,38] The test site's concentrations were more in line with Letourneau's et al.'s 2010 wintertime study (up to 4010 ppm)[11] and Donham et al.[25] (up to 4500 ppm). While the American Thoracic Society reports that carbon dioxide exposures have been considered in agricultural health studies[50], these exposures may have less impact on adverse health than other gases, namely $NH_3$ and $H_2S$, and dusts. While the current regulatory and consensus standards focus on health effects above 5000 ppm, levels between 1000 and 2000 are associated with complaints of drowsiness and between 2000 and 5000 may be associated with headaches, sleepiness, and reduced concentration.[51] The relationship between adverse health outcomes and exposures to low $CO_2$ concentrations, namely between 1000 ppm (ASHRAE recommendation for comfort/odor control in buildings)[52] and the 5000 ppm (ACGIH 8-hour threshold limit value)[53], are unclear. However, there are data that indicate that these concentrations in combination with other swine CAFO contaminants, are associated with adverse respiratory outcomes in this population.

Early simulations of contaminant concentrations in a farrowing room matching this test site's dimensions and operations[49] identified similarly high $CO_2$ concentrations, even though the simulations used a much warmer outdoor winter temperature than this field study experienced. While varying ventilation system operations in attempt to dilute simulated $CO_2$ over the winter were ineffective, because bringing fresh but cold fresh air into the room required additional heater operation, simulations examined the effect of eliminating the gas as a byproduct of the heater and achieved $CO_2$ concentrations below the Donham recommendations of 1540 ppm. Most swine operations throughout the Midwest region rely on heaters that do not vent combustion gases out of the occupied spaces, and future work should examine whether a suitable vented heater can be deployed to reduce this concentration within the CAFO.

## Conclusion

This project demonstrated that a standard industrial ventilation system with filtration dust control and clean air recirculation (to limit heating costs) can be used to reduce particle concentrations in an agricultural setting without increasing the concentrations of other hazardous gases. The 0.47 $m^3\ s^{-1}$ (1000 cfm) filtration unit reduced dust concentrations by 33% (inhalable) and 41% (respirable) averaged over the season while requiring no maintenance. These observations represent a first step in applying standard equipment used in other industrial operations to the agricultural sector. Although health hazard assessments were not incorporated into the present study, a recirculating ventilation system represents a technically and economically feasible intervention that may prevent the decline of respiratory health for workers in CAFO. Future deployment in production operations, combined with efficiency studies and health effects studies, are needed to examine the effectiveness of reducing dust exposures (recirculating ventilation) and carbon dioxide (heater substitution).

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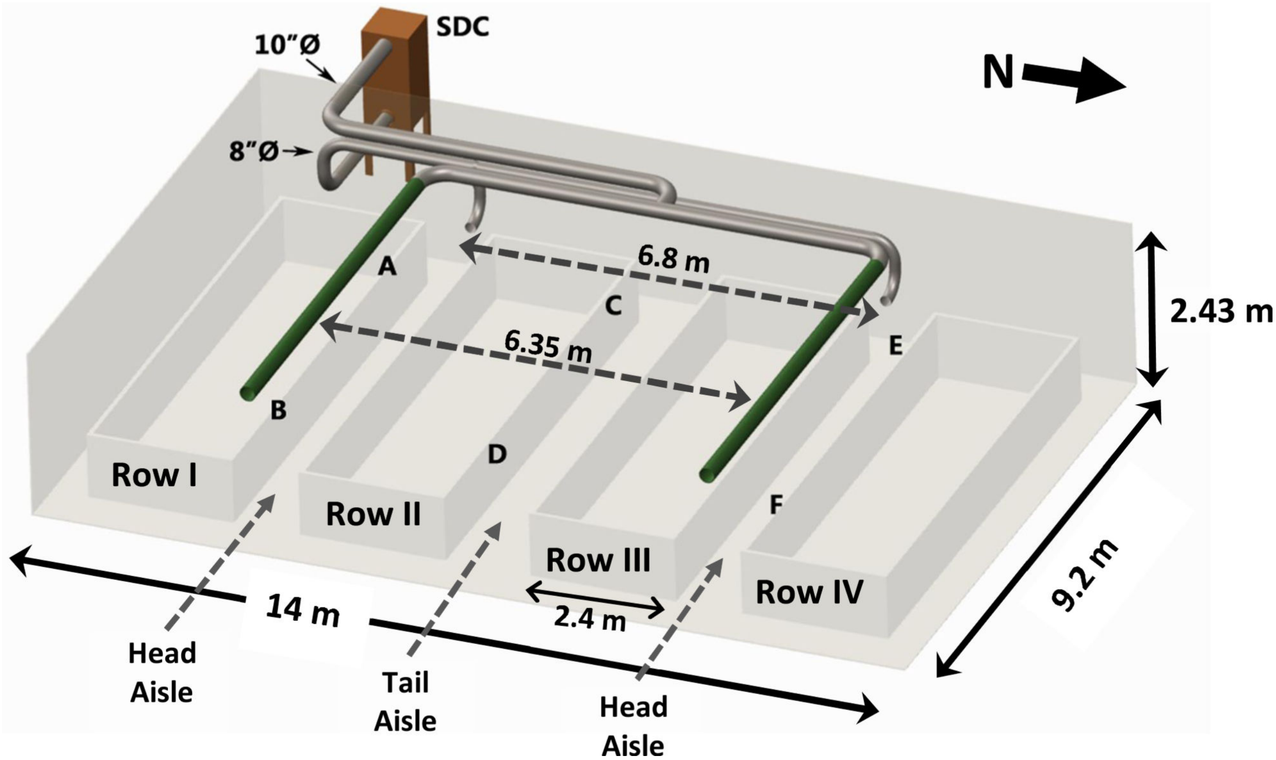


**Figure 1.**
Layout of test site.

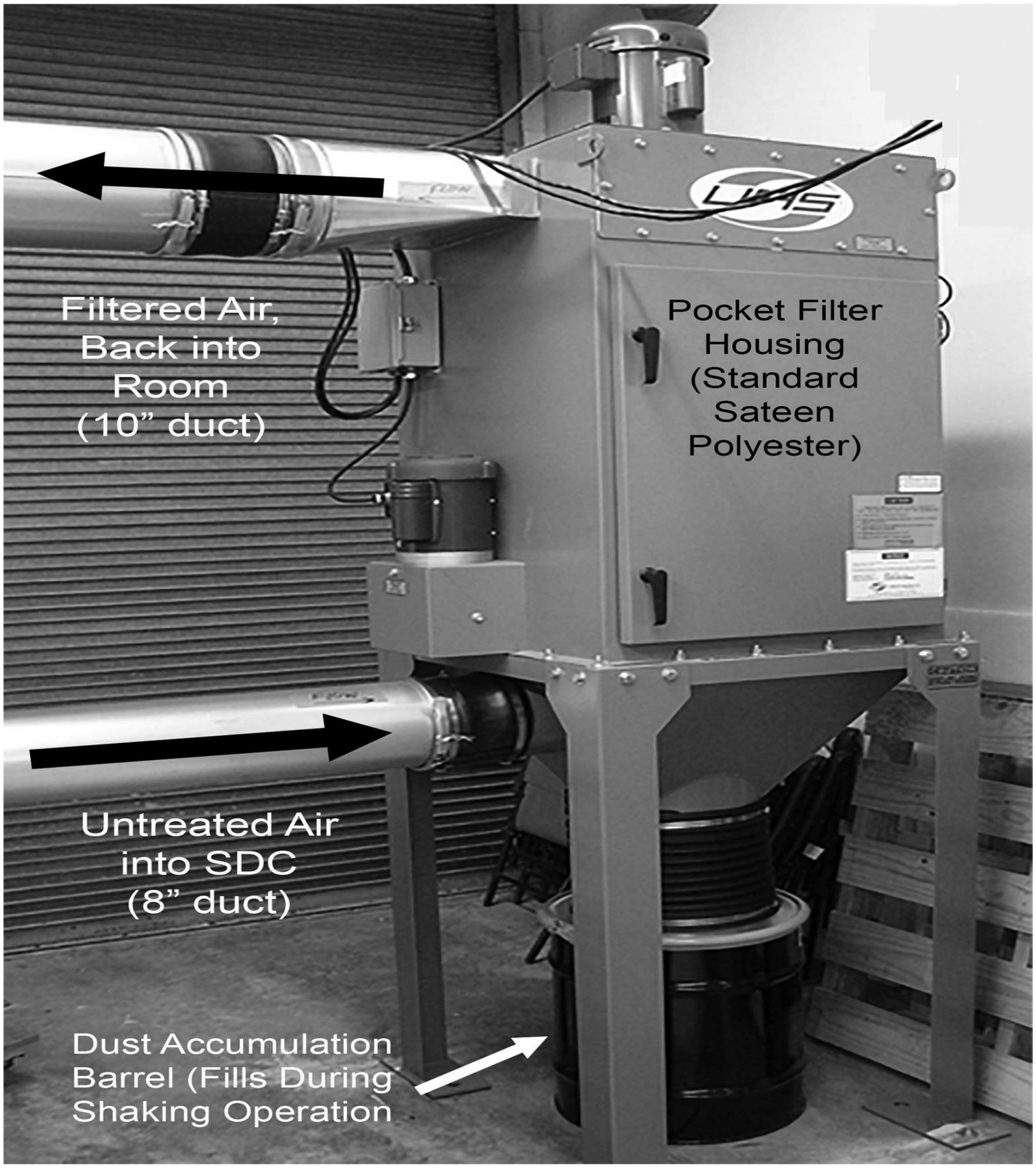


**Figure 2.**
Annotated image of Shaker Dust Collector (SDC) prior to field deployment.

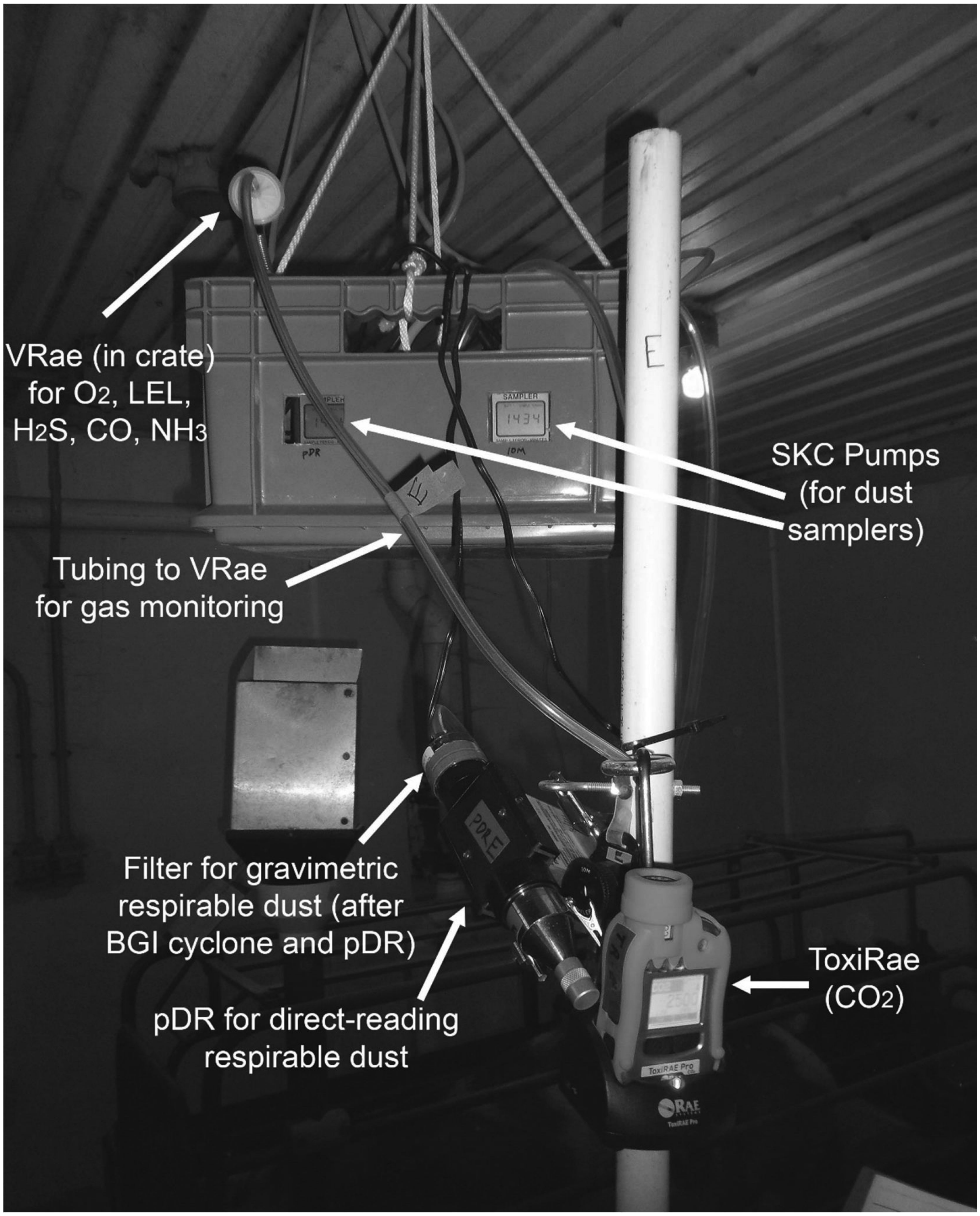


**Figure 3.**

Sampler deployment (Position E). Inlets all positioned at 1.5 m above the floor. The ToxiRae, pDR and BGI cyclone, and IOM cassette were attached to the pole. The tubing from the VRae was fed through the bolt.

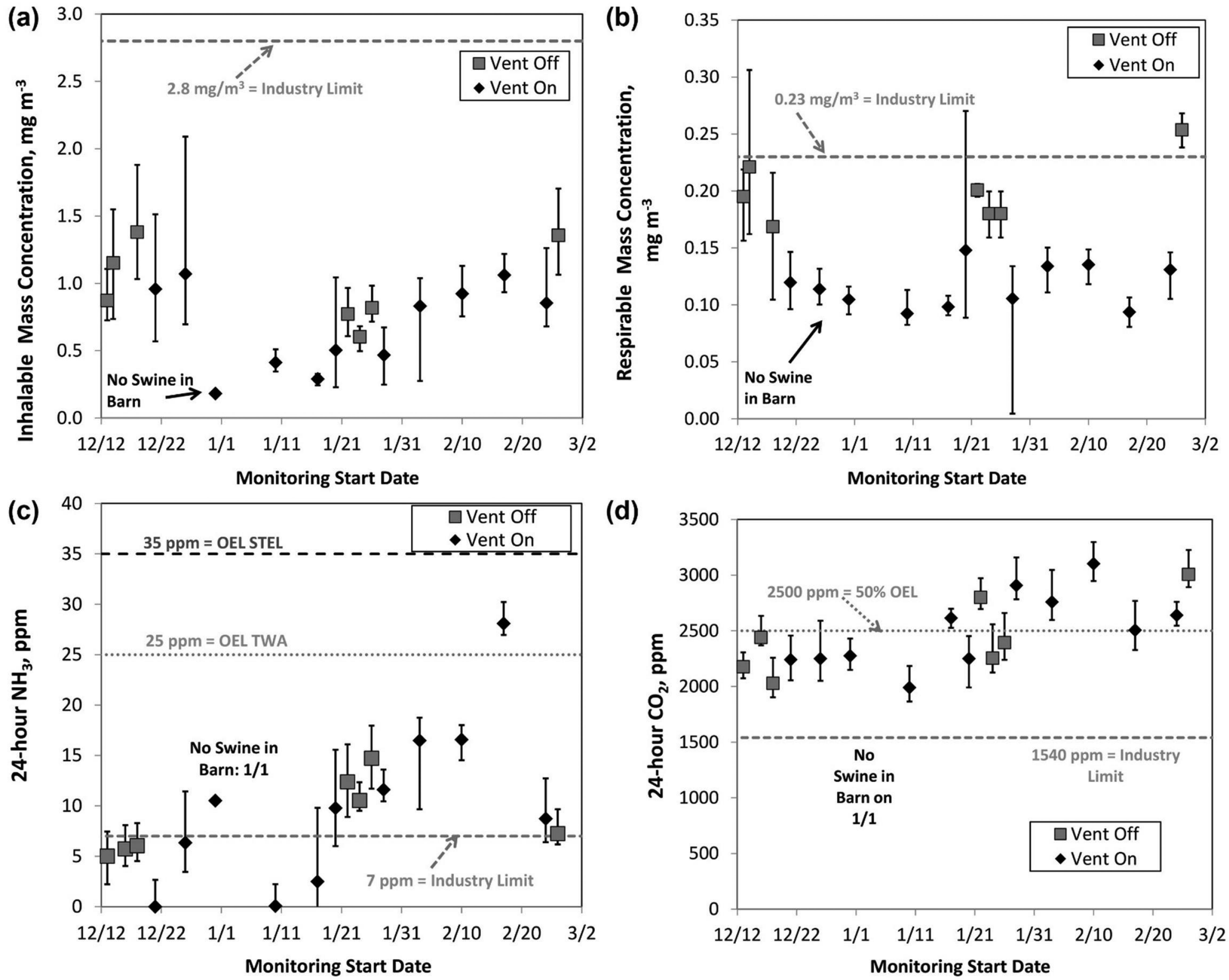


**Figure 4.**

24-hour average concentration by sample date for (a) inhalable dust, (b) respirable dust, (c) ammonia ($NH_3$) and (d) carbon dioxide ($CO_2$). Error bars represent the range of concentrations, over all positions in the barn, on the given day.

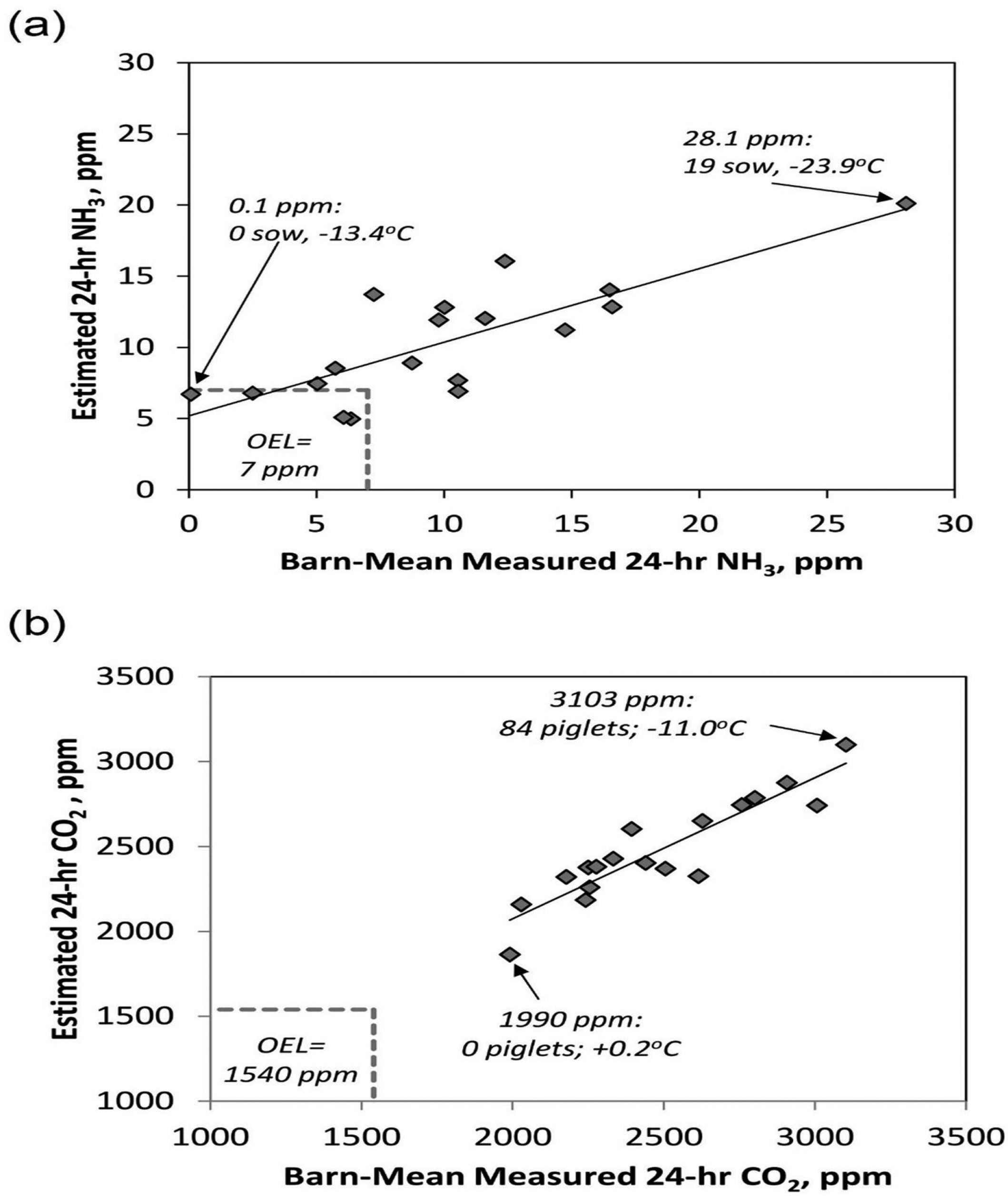


**Figure 5.**
Fitted concentration estimates by production (sow and piglet counts) and outdoor temperatures (24-hour average) for (a) $NH_3$ and (b) $CO_2$.

**Table I**

Summary of air quality monitoring equipment

| Contaminant | Device | Operation | Calibration |
|---|---|---|---|
| Inhalable Dust, mg $m^{-3}$ | IOM – plastic internal cassette with 5 µm PVC filters | 2 Lpm, PCXR4 pumps on AC power (SKC, Eighty Four, PA) | Bios DryCal |
| Respirable Dust, mg $m^{-3}$ | BGI GK2.69<br>Cyclone with 5 µm PVC filters PVC filters | 4.2 Lpm, PCXR4 pumps on AC power | Bios DryCal |
| Respirable Dust, direct-reading, mg $m^{-3}$ | pDR-1200 (Thermo-Electron Corp, Waltham, MA) | 4.2 Lpm, 60-sec logging interval, connected to respirable dust gravimetric train, above | Bio DryCal |
| Oxygen, %<br>Flammable Gas, % LEL<br>Hydrogen Sulfide, ppm<br>Carbon Monoxide, ppm<br>Ammonia, ppm | VRae (Rae Systems, San Jose, CA) | 0.4 Lpm pump with 60-sec logging interval | $O_2$ = 20.9%<br>LEL = 50% (2.5% methane)<br>$H_2S$ = 25 ppm<br>CO = 50 ppm<br>$NH_3$ = 25 ppm |
| Carbon Dioxide, ppm | ToxiRae (Rae Systems, San Jose, CA) | 60-sec logging interval | $CO_2$ = 2.5% ppm<br>Zero gas=99.9999% $N_2$ |
| Temperature, humidity | VelociCalc (Model 9555-X, TSI Inc., Shoreview, MN) | 60-sec logging interval | Co-located with NIST traceable temperature probe, pre- and post-deployment. |
| Outdoor Temperature | Cedar Rapids<br>Airport<br>Meterorological Data | - | - |

### Table II

Occupational exposure limits (OELs) for swine farrowing barn contaminants

| Threshold | Inhalable Dust, mg/m$^3$ | Respirable Dust, mg/m$^3$ | CO, ppm | $H_2S$, ppm | $CO_2$, ppm | $NH_3$,* ppm |
|---|---|---|---|---|---|---|
| OEL | 10 | 3 | 25 | 1 | 5000 | 25 |
| Industry Recommendations | 2.8 | 0.23 | - | -- | 1540 | 7 |

OELs are based on 8-hour ACGIH TLVs[54]; Industry recommendations from Donham et al.[25]

**Table III**

Mean (standard deviation) and sample count (N) of study factors over 18 24-hour sample days.

| Variables | 8-hour Mean (SD), Using Barn-Averaged Data: System Off | 8-hour Mean (SD), Using Barn-Averaged Data: System On | 8-hour Mean (SD) Using Data from 6 Positions: System Off | 8-hour Mean (SD) Using Data from 6 Positions: System On | 24-hour Mean (SD) Using Data from 6 Positions: System Off | 24-hour Mean (SD) Using Data from 6 Positions: System On | p for non-parametric 24-hr difference testing |
|---|---|---|---|---|---|---|---|
| Inhalable Dust (gravimetric), $mg/m^3$ | - | - | - | - | **1.01 (0.68) N=38** | 0.68* (0.39) N=60 | <0.001 |
| Respirable Dust (gravimetric), $mg/m^3$ | - | - | - | - | **0.20 (0.04) N=41** | 0.12* (0.03) N=65 | <0.001 |
| Respirable Dust (pDR), $mg/m^3$ | **0.067 (0.024) N=21** | **0.038 (0.014) N=33** | *0.068* (0.027) N=115* | 0.039* (0.015) N=189 | **0.070 (0.26) N=40** | **0.039 (0.014) N=65** | **<0.001** |
| $NH_3$, ppm | 8.8* (3.8) N=21 | 11.0* (7.6) N=33 | 8.4* (4.3) N=114 | 9.9* (7.2) N=169 | 8.6* (3.9) N=37 | 10.2* (7.0) N=56 | 0.22 |
| $CO_2$, ppm | **2440 (360) N=21** | **2500 (340) N=33** | 2440* (370) N=126 | 2510* (360) N=193 | **2440 (350) N=42** | **2500 (350) N=65** | **0.33** |

*The data within this set were not normally distributed. ***Italics bold*** indicate that ln(conc) was normally distributed.

## Table IV

Average livestock occupancy in crates by sampling stations A through F.

| | Head Aisle | | Tail Aisle | | Head Aisle | |
|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** |
| **Sows:** Percent of days neighboring crates were occupied | | | | | | |
| System Off (N=7) | 57 | 54 | 89 | 89 | 61 | 100 |
| System On (N=11) | 64 | 64 | 86 | 86 | 73 | 91 |
| All days (N=18) | 61 | 60 | 88 | 88 | 68 | 94 |
| **Piglets:** Percent of piglet production in neighboring crates | | | | | | |
| System Off (N=7) | 8 | 9 | 17 | 32 | 20 | 44 |
| System On (N=11) | 17 | 15 | 25 | 30 | 19 | 34 |
| All days (N=18) | 13 | 12 | 22 | 31 | 19 | 38 |

## Table V

Significance levels (p) of barn concentration reductions using new ventilation system.

| Contaminant | All Data, System On vs Off* | Concentrations by Position | | Concentration by Shift | |
|---|---|---|---|---|---|
| | | System On | System Off | System On | System Off |
| *Tukey-Kramer p-value for tests indicated:* | *Wilcoxon 2-sample* | *Least Squares Multiple Comparison* | *Least Squares Multiple Comparison* | *Least Squares Multiple Comparison* | *Least Squares Multiple Comparison* |
| Inhalable Dust (gravimetric), $mg/m^3$ | <0.001* | **> 0.71** | > 0.72* | - | - |
| Respirable Dust (gravimetric), $mg/m^3$ | <0.001* | **> 0.61** | > 0.36* | - | - |
| Respirable dust (pDR), $mg/m^3$ | **<0.001** | **> 0.99** | **> 0.23** | > 0.15* | 0.002* (1 > 2) |
| $NH_3$, ppm | 0.13* | **> 0.63** | > 0.72* | 0.039* (3 > 1) | > 0.19* |
| $CO_2$, ppm | 0.32 | **> 0.58** | **> 0.23** | > 0.69* | > 0.44* |
| *Non-Parametric Tests, Kruskal-Wallis p-values* | | | | | |
| Inhalable Dust (gravimetric), $mg/m^3$ | **<0.001** | 0.72 | **0.95** | - | - |
| Respirable Dust (gravimetric), $mg/m^3$ | **<0.001** | 0.71 | **0.020** (D < E) | - | - |
| Respirable dust (pDR), $mg/m^3$ | <0.001 | 0.87 | 0.20 | **0.30** | ***0.006*** (1 > 2) |
| $NH_3$, ppm | **0.22** | 0.47 | **0.76** | **0.099** | **0.34** |
| $CO_2$, ppm | **0.33** | 0.55 | 0.35 | **0.78** | **0.46** |

Notes: Asterisk (*) indicates data were not normally distributed and non-parametric testing results should take precedence for interpretation. **Data in bold** present the optimal analysis to interpret differences between concentrations. Parenthetical letters indicate Positions identified as different; parenthetical numbers indicate Shifts identified as different.